New Model of Raman Spectra in Laser-Produced Plasma

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Observations of Raman scattering in laser-produced plasma can be explained by incoherent Thomson scattering, with a greatly enhanced "plasma line." Reversed-slope velocity distributions in the underdense region are produced by hot-electron pulses originating near the quarter-critical surface ($n_c/4$). The model explains the two gaps in the Raman spectrum, the correlation of scattering "onset" with that of instability at $n_c/4$, the "scintillation" in frequency and time, and the weak angular variation. An "upscattered" frequency band is predicted and has been verified by experiment.

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Recent experiments have studied the spectral and temporal distribution of scattered light from planar and spherical laser-produced plasmas.[1-4] The reradiation at $\omega_0/2$ (where ω_0 is the incident frequency) shows two relatively sharp increases when plotted as a function of increasing incident intensity.[2] These rises can be interpreted as the onset of the two-plasmon instability ($2\omega_p$) and then the absolute stimulated Raman scattering (SRS-A), respectively, occurring near the quarter-critical ($n_c/4$) surface in the plasma. Observation of a separated broad band of radiation, lying in frequency between ω_0 and $\omega_0/2$, has been interpreted as evidence of the onset of the convective stimulated Raman instability (SRS-C) originating in the underdense region below $n_c/4$. The upper limit of this band corresponds to scattering from regions whose density is as low as $0.05n_c$ and the lower part to regions with densities as large as $0.2n_c$.

There have remained some difficulties in this SRS-C interpretation. One is the observation that the broadband radiation sets in at almost the same intensity as the SRS-A, despite the theoretical prediction that the convective threshold should be considerably higher if both instabilities occur in the plasma with comparable density scale lengths. A second is the existence of the two gaps in the spectrum: one between the lower end of the band and $\omega_0/2$, and the other between the upper end and ω_0. While the upper gap can be understood on the basis of Landau damping,[4] the lower gap requires invocation of density steepening near $n_c/4$.[2] This is despite the fact that the lower gap is always present in a variety of experimental situations, some of which show little evidence for the presence of steepening.

A third difficulty is that some limited observations[5] of the azimuthal angular distribution show little variation, while SRS-C calculations, using spatial gain from noise sources, incorporate angular terms in the exponential factors[4] and lead to the prediction of strong peaking out of the plane of polarization. Finally, a fourth problem is that spectrally and temporally resolved data[2,4] show that the scattering in the band region does not generally occur over large regions of frequency and/or time simultaneously. The effect seems to scintillate, suggesting contributions from localized regions during brief periods of time.

One approach to explain these difficulties has been to invoke the creation of filaments by self-focusing of hot spots of the incident light.[3,4] The greatly increased light intensity in the filament can exceed the threshold for SRS-C. The scintillation in time may be due to instability of the filaments themselves, while the spatial localization may be due to the existence of a density peak along the filament length.

In this note we propose an alternative explanation of the spectral band based on ordinary incoherent Thomson scattering. It is well known that the incoherent scattering of radiation from plasma[6] exhibits a number of interesting features, including a Doppler broadening characteristic of the ion temperature near the incident frequency ω_0, and a sharp intense "plasma line" near the frequencies $\omega_0 \pm \omega_p$ (Raman scattering). While the total scattered power in the plasma line is usually small compared with the incident power for a Maxwellian distribution of electrons, it can be much enhanced as noted by Perkins and Salpeter.[7] In certain regions of the ionosphere, a two-temperature electron distribution is created in the daytime by absorption of the solar ultraviolet and x rays, producing energetic photoelectons in the 1–30 eV range while the bulk distribution has a temperature of only about 0.2 eV. This velocity distribution can result in increases in the plasma line intensity by factors of 50 to 100.

Even more enhancement may occur in the underdense corona of a laser-irradiated target. In this case, the sources of hot electrons are the $2\omega_p$ and SRS-A instabilities occurring near the $n_c/4$ surface. The hot-electron pulses resulting from the intermittent breaking of plasma waves near $n_c/4$ move in or out and are reflected by the sheaths, thus producing transient local velocity distributions which can be modeled as a Maxwellian with temperature T_c for the bulk of the electrons, together with a narrow moving pulse of "hot" electrons moving in or out in the radial direction.

The resultant scattering intensity is evaluated by the methods of Ref. 7, including integration over the plasma volume. The principal contribution to the integral is from the appropriate "plasma line." The expression for the fractional scattered power has the usual Thomson-scattering angular variation and the usual magnitude, multiplied by a shape factor S which is

$$S=\frac{(E_p/T_c)^{1/2}\exp(-E_p/T_c)+(T_c/E_p)\bar{\nu}/\omega+\epsilon\alpha^{1/2}y\exp[-\alpha(y-1)^2]}{\bar{\nu}/\omega+(E_p/T_c)^{3/2}\exp(-E_p/T_c)+\epsilon\alpha^{3/2}y^2(y-1)\exp[-\alpha(y-1)^2]}. \quad (1)$$

Here $E_p\equiv\frac{1}{2}m(\omega/k)^2$, $\omega=\omega_0-\omega_s$, $k=|\vec{k}_0-\vec{k}_s|$, with ω_s and $\vec{k}_s$ the frequency and wave vector of the scattered electromagnetic wave. The electron-ion collision frequency is denoted by $\bar{\nu}$ and the ratio of the hot-electron density to the cold-electron density by ϵ (assumed small). Also $\alpha=3T_h/2T_c$ and $y^2=2E_pk^2/3k_r^2T_h$ with T_h representing the equivalent temperature associated with the central velocity v_h of the moving electron pulse, $3T_h=mv_h^2$, and k_r the radial component of $\vec{k}$. Equation (1) is not valid for $\omega_s=\omega_0$ since it has been assumed that $\omega/k >> (2T_c/m)^{1/2}$.

Major enhancement of the reflected power can occur for ω_s and k_s such that the corresponding radial component of the plasma-wave phase velocity, ω/k_r, falls on the increasing-slope portion of the "hot"-electron pulse, i.e., $y<1$. If ϵ is large enough, the denominator in Eq. (1) will then become small or negative. The homogeneous dressed test-particle model is invalid in this limit, but it is certain that very large enhancements will occur. A proper calculation of the scattered intensity will require solution of a nonlinear problem.

One finds that the two gaps in the spectrum occur in a natural way once ϵ exceeds this critical level. For ω_s near $\omega_0/2$, the plasma-wave phase velocity is high, the resistive terms dominate in Eq. (1), and one finds $S=O(10^{-2})$ for parameters appropriate to the experiments described in Ref. 2 ($T_c=1$ keV). The resultant scattered intensity is below the experimental detection level by a factor of 10^2–10^3. Again, when ω_s approaches ω_0 [but not so close that Eq. (1) is invalid] the phase velocity becomes small enough that the Landau damping term of the cold electrons dominates and again one finds $S=O(10^{-2})$. These same considerations predict a separated band in the upscattering regions between ω_0 and $2\omega_0$ (but not symmetrical to the lower one since k_s will be larger).

If one defines the enhanced radiation intervals as corresponding to regions where the denominator of Eq. (1) vanishes or is negative, it is easy to explore the dependence on various parameters. Using a computer, we have studied the variation of the bands with ϵ, T_c, T_h, and scattering angle θ. An example of these results are shown in Figs. 1 and 2. In Fig. 1, the beginning of "downscattering" is seen when ϵ exceeds 10^{-4}. The "upscattering" sets in when ϵ exceeds 10^{-3}. These results are for $T_c=1$ keV, $T_h=18$ keV, and an internal scattering angle of 90°. Note the broadening of the bands as ϵ increases. Figure 2 illustrates shifting and broadening of the bands as the internal scattering angle is varied, for $T_c=1$ keV, $T_h=18$ keV, and $\epsilon=5\times10^{-3}$. We have also noted smaller shifting with variation of T_h, and relatively little with variation of T_c. Recent experimental observations[8] have ob-

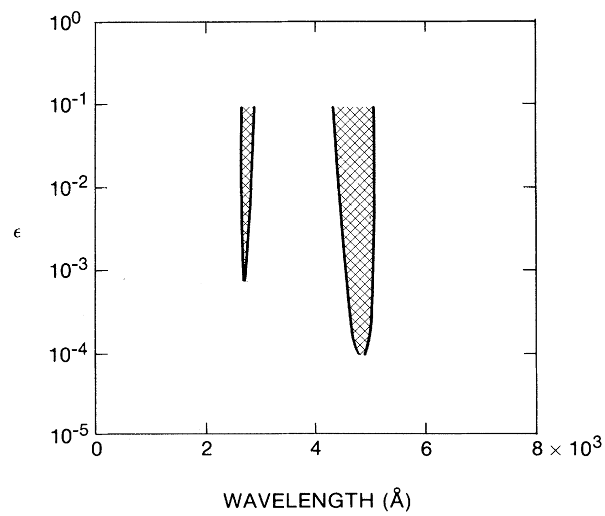

FIG. 1. Variation of enhanced Raman scattering band (hatched area) with ϵ, the ratio of hot-electron density to cold-electron density. This is for scattering at an (internal) angle of 90° with $T_h=18$ keV, $T_c=1.0$ keV, and an incident wavelength of 3510 Å.

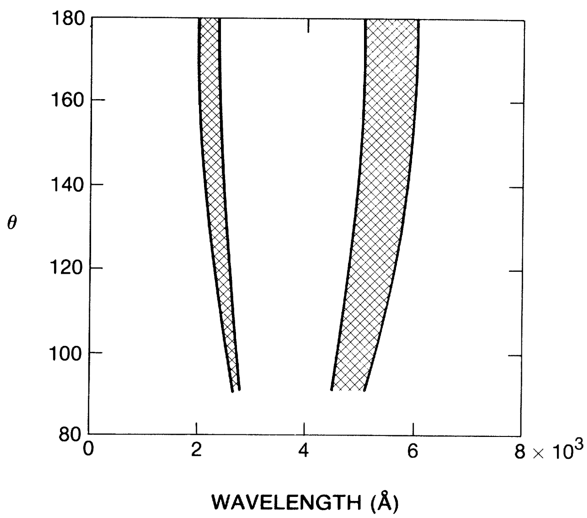

FIG. 2. Variation of enhanced Raman scattering band (hatched area) with (internal) angle of scattering; $\epsilon = 5\times10^{-3}$, where ϵ is the ratio of hot electron to cold electron density, $T_h = 18$ keV, $T_c = 1.0$ keV, and an incident wavelength of 3510 Å.

served the upscattered band as well as the downscattered band, close to where these calculations predict them to be. In fact, a previously unexplained feature in the region between $\frac{3}{2}\omega_0$ and $2\omega_0$, seen in six-beam experiments (at the Laboratory for Laser Energetics) on Omega,[5] was readily fitted by this theory. It is worth noting that the SRS instability cannot give rise to upscattering in this region, even by indirect means. Additional agreement has been made with experiments on Shiva and Argus (see Figs. 3 and 9 of Ref. 1) and with carbon foil targets on GDL.[9]

Our model also accounts for the other features discussed earlier. The coupling between the onset of the Raman spectrum and the onset of SRS-A is clear since it is presumably the hot electrons from the SRS-A at $n_c/4$ which establish the reversed-slope plasma medium in the subcritical region (i.e., raise the value of ϵ to the critical point). The scintillation clearly arises from the turbulent pulsed nature of this same source. The azimuthal angular distribution of this ordinary Thompson scattering is relatively gentle compared to the SRS-C. Even at 90°, it is simply $\sin^2\phi$.

In summary, we propose a new model of the Raman spectra observed in laser experiments in inhomogeneous plasma. The scattering is due to ordinary incoherent Thompson scattering (via a greatly enhanced "plasma line"). The wakes of the incoherent "dressed" electrons are enlarged as the result of a reversed-slope velocity distribution in the subcritical region created by bursts of hot electrons moving out from the quarter-critical surface and created there by breaking of waves resulting from the SRS-A or $2\omega_p$ instabilities. A unique feature of the model is the prediction of appreciable "upscattering," the existence of which has been experimentally observed.

We note that Estabrook and Kruer[10] have seen an anomalously high level of Thomson scattering in recent simulation studies. It is not clear what the origin of this high noise level is.

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